Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation

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ABSTRACT

Land subsidence in Las Vegas, Nevada, United States, between April 1992 and December 1997 was measured using spaceborne interferometric synthetic aperture radar. The detailed deformation maps clearly show that the spatial extent of subsidence is controlled by geologic structures (faults) and sediment composition (clay thickness). The maximum detected subsidence during the 5.75 yr period is 19 cm. Comparison with leveling data indicates that the subsidence rates declined during the past decade as a result of rising ground-water levels brought about by a net reduction in ground-water extraction. Temporal analysis also detects seasonal subsidence and uplift patterns, which provide information about the elastic and inelastic properties of the aquifer system and their spatial variability.

INTRODUCTION

Land subsidence caused by compaction of overdrafted aquifer systems is a worldwide problem in agricultural and urban areas heavily dependent on ground-water supplies (Poland, 1984). The overdraft of aquifer systems containing fine-grained silt and clay layers (aquitards) results in a vast, one-time release of "water of compaction" from the aquitards. During this typically slow drainage process, permanent land subsidence occurs primarily due to the irreversible (inelastic) compaction of aquitards. A lesser amount of subsidence occurs as recoverable (elastic) compression of the coarse-grained sand and gravel deposits (aquifers) and the aquitards. These processes are described by the aquitard-drainage model (Terzaghi, 1925; Tolman and Poland, 1940; Holzer, 1984).

Las Vegas (Spanish for "the meadows"), Nevada, United States, was once a lush desert oasis where water flowed from springs of an artesian (confined) aquifer-system. Ground water is currently pumped at a rate two to three times more than the natural recharge, and constitutes about 25% of the present water supply; the remainder is imported from the Colorado River. Persistent overdraft of the aquifer system since about 1950 (Mindling, 1971) lowered water levels throughout the Las Vegas Valley, in some places in excess of 90 m (Wood, 1999). In response, parts of the valley have subsided more than 2 m since 1935 (Maxey and Jameson, 1948; Bell, 1981). Related ground failures have caused extensive structural damage. Historically, subsidence has been measured only by infrequent conventional leveling surveys (Bell, 1981; Bell and Price, 1991) on sparsely distributed benchmarks.

APPROACH

We use interferometric synthetic aperture radar (InSAR) to obtain spatially detailed maps of ground-surface deformation. This technique has been applied previously to investigate earthquakes (Massonet et al., 1993), volcanoes (Masson et al., 1995), and land subsidence (Massonet et al., 1997; Fielding et al., 1998; Galloway et al., 1998). Two synthetic aperture radar (SAR) images acquired by the European Earth Remote-Sensing (ERS) satellites with a temporal separation of one year or more are combined to form a change interferogram. The phase of the signal contains information about coherent displacements of all scatterers imaged by the radar, and about the topography. The topographic component is removed using a scaled topography interferogram of February 8–9, 1996 (three- or four-pass method, Zebker et al., 1994a); the scaling factor is derived from the Delft orbits (Scharro et al., 1998). One cycle of phase (1 fringe) represents 28 mm of radar line-of-sight (range) displacement, and 31 mm of vertical ground displacement. In this study we assume that all deformation is vertical.

A typical accuracy for a phase measurement is about one-fifteenth of a cycle (averaging 20 pixels, e.g., Zebker et al., 1994b), or 1.6 mm range displacement. The accuracy of relative deformation measurements is generally a factor of two to five times smaller than the accuracy of phase measurements, because of signal delays due to lateral variations in atmospheric water vapor (Hanssen et al., 1999). The arid climate of Las Vegas reduces atmospheric effects. Comparison with a U.S. Geological Survey digital elevation model showed no atmospheric disturbances in the interferogram used for the removal of topography. Because we are interested in smaller scale (<10 km) displacement signals, we safely remove larger scale (>10 km) phase ramps due to orbital uncertainties. Taken together, this suggests an accuracy of the InSAR measurement of 2–4 mm for range displacement. The principal sources of uncertainty are (1) the loss of signal coherence in the change interferogram in areas where the radar backscatter characteristics have changed, and (2) the inability to resolve large displacement gradients because the phase is measured modulo 2π.

RESULTS

An InSAR generated map of subsidence in the Las Vegas Valley between April 1992 and December 1997 (Fig. 1A) delineates two main features, a subsidence bowl in the northwest and a north-northwest–oriented, elongated subsidence zone in the center of the valley. The northwest subsidence bowl is semicircular and includes the maximum measured subsidence (190 mm). The southeastern boundary is aligned along the Quaternary Eglington fault. Similarly, the central subsidence zone also is bounded by several mapped faults.

A comparison between InSAR measurements and leveling measurements (Fig. 1B) shows general agreement. The larger displacement gradients measured by leveling may be due to the different time intervals of the two measurements. A comparison of 1980–1991 leveling data with three interferograms (Fig. 1C) indicates that the rate of subsidence has been decreasing since 1992. Along a 0.5 km section of line 1, the rate of differential subsidence across the Eglington fault was 15 mm/yr during 1996–1997, compared to 20 mm/yr during 1992–1993 and 50 mm/yr during 1980–1982.

Four differential interferograms for different time periods between April 1992 and December 1997 (Fig. 2) reveal spatial detail about the temporal variation of subsidence. In the northwest subsidence bowl, the general pattern of displacement is repeated throughout the 5.75 yr period, but the rate of displacement decreases with time. The northwest subsidence bowl shows about 70 mm of range displacement (2.5 fringes) in the April 1992–November 1993 interferogram (Fig. 2A), but only 40 mm (1.5 fringes) in the November 1993–February 1996 interferogram (Fig. 2B), which spans a 1.5 times longer time interval. The central subsidence zone is most extensive in the April 1992–November 1993 interferogram (Fig. 2A). In the November 1993–February 1996 interferogram (Fig. 2B), this central subsidence zone is instead represented as localized areas of both increasing (relative subsidence) and decreasing range displacement (relative uplift).

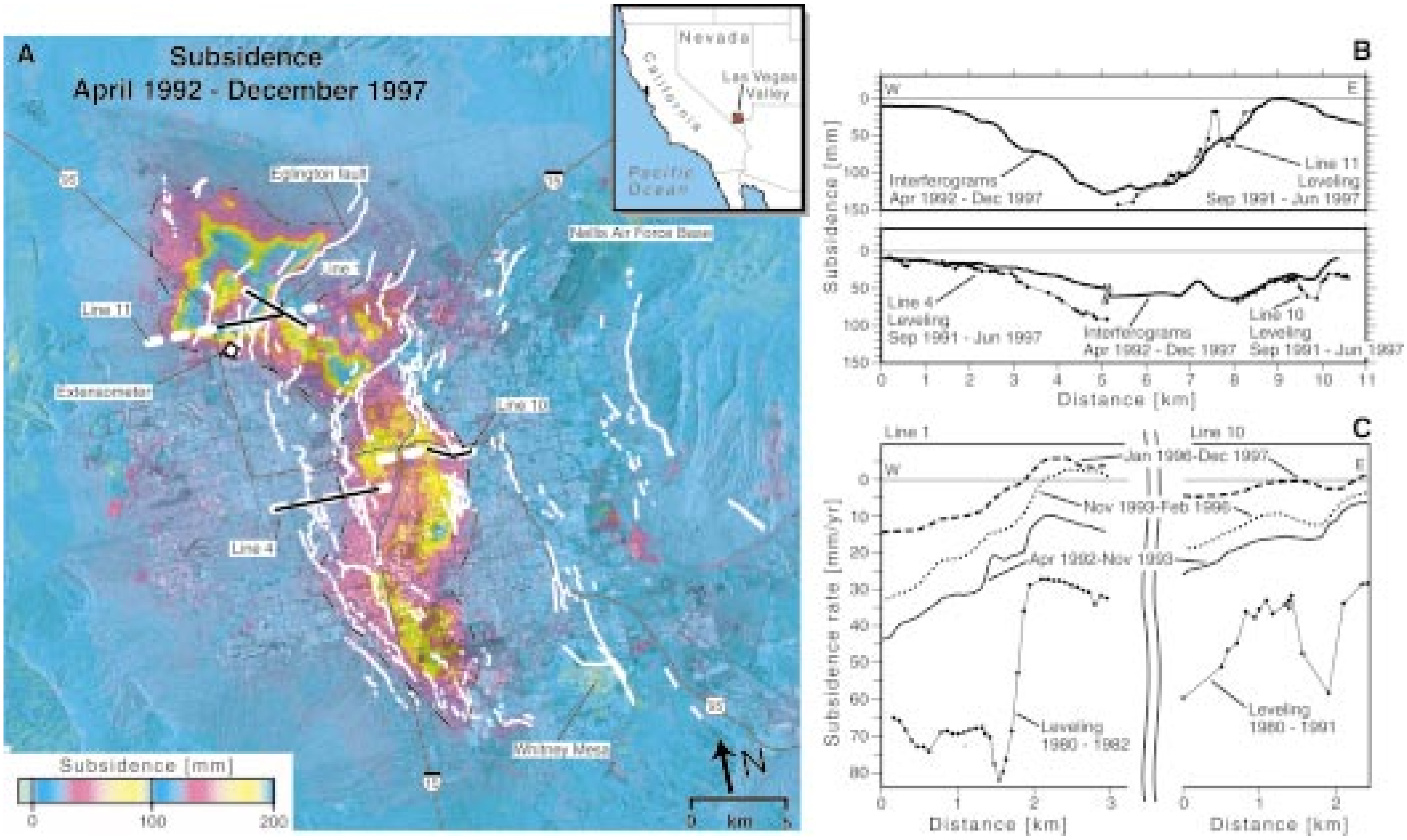

Figure 1. A: Subsidence in Las Vegas Valley between April 1992 and December 1997, obtained from interferograms (Fig. 2, A, B, and C) by unwrapping phases using Zebker and Lu (1998) algorithm, projecting range displacement onto equivalent vertical displacement, and summing interferograms; and mapped surface faults. Dashed line indicates 30 mm subsidence contour. Pixel size is 1600 m^2. One color cycle indicates 100 mm of displacement. Stable landforms (bedrock) are assigned zero subsidence. Phase signatures along urban margins may be artifacts related to loss of coherence due to construction. B, C: Subsidence and subsidence rates as measured by interferograms (thick dashed white lines in A) and leveling (solid black lines in A). Leveling data are relative and shifted to arbitrary value. Random error of leveling data from difference between backward and forward runs is 5–10 mm.

The November 1993–February 1996 interferogram (Fig. 2B) also shows several areas of relative uplift, e.g., at Whitney Mesa, at Nellis Air Force Base, southeast of the Eglington fault, and near the eastern boundary of the central subsidence zone. These patterns could be confused with atmospheric artifacts, but their repeatable presence (although smaller) in interferograms constructed from different SAR images (e.g., in the January 1996–December 1997 interferogram, Fig. 2D) indicates that the displacements are real.

Data acquired since 1994 from a borehole extensometer (Fig. 3) near the northwest subsidence bowl provide insight into the simultaneous elastic and inelastic deformation of the aquifer system. During the summer season when water levels decline 10–15 m, aquitards and aquifers undergo a net compaction of 5–7 mm. During the winter season when water levels recover, any residual inelastic compaction in the aquitards generally is compensated for by elastic expansion in the aquifers and aquitards, resulting in minimal net vertical surface displacement (generally 0–2 mm subsidence, 2 mm uplift in winter 1997–1998). Residual compaction is the difference between the compaction that occurred when water levels first dropped below the past minimum water level (preconsolidation stress) and the compaction that would ultimately occur in the new equilibrium.

The aquitard-drainage model suggests a spatial correlation between land subsidence, water-level decline, and aquitard thickness. From predevelopment to 1990, water levels declined significantly throughout the valley (Fig. 4A); the maximum decline was more than 90 m in the area west of the central subsidence zone. Since 1990, ground-water levels generally have recovered (Fig. 4B), except in the northern part of the northwest subsidence bowl, in response to a reduction of net ground-water extraction. This net reduction has been achieved primarily through artificial recharge, a program initiated in 1988 by the Las Vegas Valley Water District to store imported water by injection of treated Colorado River water into the aquifer system.

A good correlation between subsidence and aggregate clay thickness in the northwest corner of the northwest subsidence bowl and in the southwest region of the central subsidence zone (Fig. 4C) suggests that clay thickness controls the extent and magnitude of subsidence here. The absence of any significant subsidence in the area of maximum water-level decline west of the central subsidence zone can be explained by a lack of significant clay thickness, and by the fact that the minimum water level was attained during the early 1970s (Wood, 1999), prior to the importation of water from the Colorado River. Here, any residual compaction may already have been realized. In the area of thickest clays to the east of the central subsidence zone, the absence of subsidence can be explained by a lack of any significant water-level decline in this region (Fig. 4A). Note the good correlation at Whitney Mesa between detected uplift and water-level decline prior to 1990 (Fig. 4A), perhaps caused by the recovery of water levels and the elastic expansion of the aquifer system after 1990.

DISCUSSION

The InSAR maps indicate that the spatial distribution of land subsidence in the Las Vegas Valley is controlled by Quaternary faults to a much greater degree than previously suspected (Bell and Price, 1991). In particular, the Eglington fault acts as a subsidence barrier. Most of the subsidence occurs on the upthrown block of this southeast-dipping normal fault, thus precluding

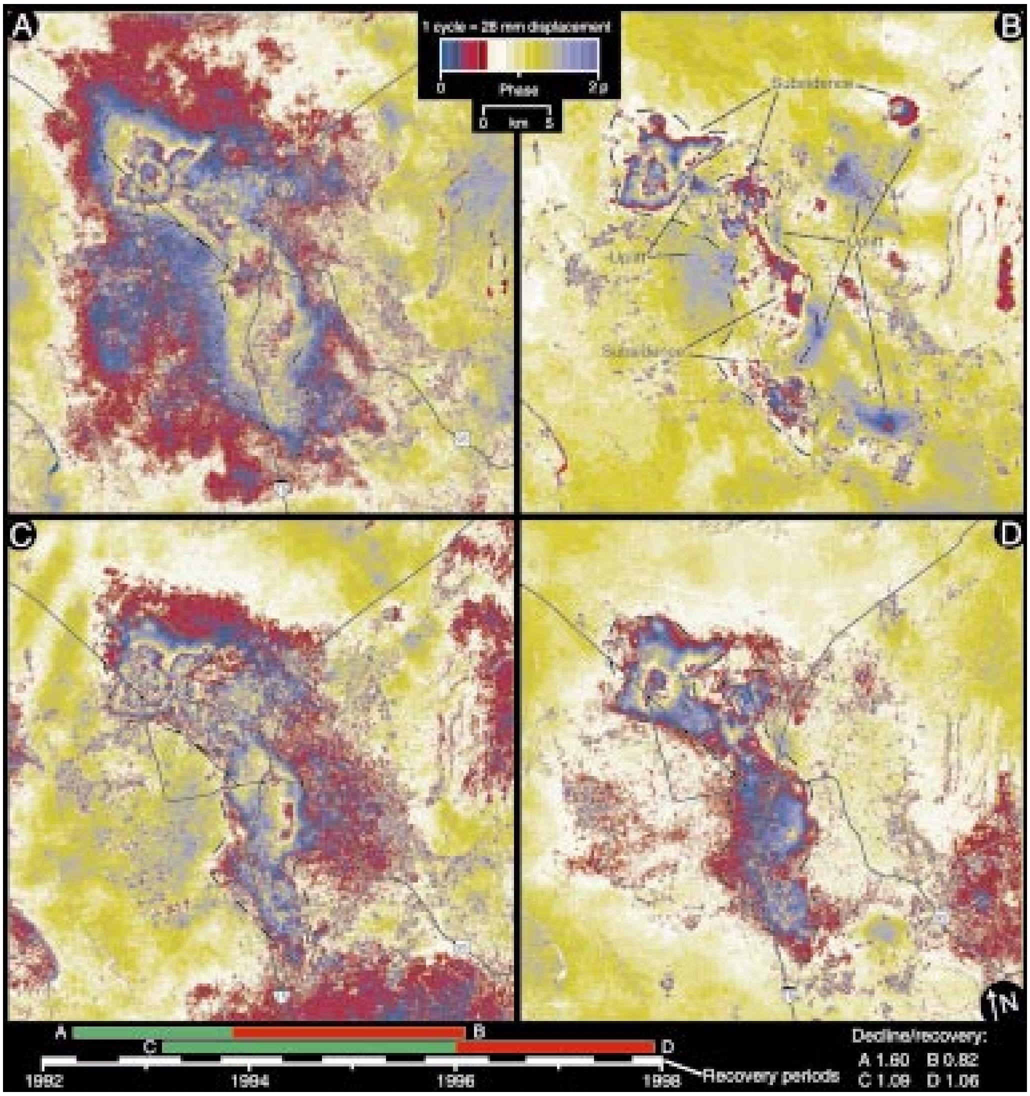

Figure 2. Differential interferograms of Las Vegas Valley for four different time periods. A: 21 April 1992–2 November 1993. B: 2 November 1993–9 February 1996. C: 2 March 1993–4 January 1996. D: 4 January 1996–5 December 1997. One cycle of phase (0–2π) represents 28 mm of change in radar line-of-sight distance or 31 mm of subsidence or uplift. Yellow represents zero range displacement. Yellow-red-blue is in direction of increasing range displacement (subsidence), yellow-blue-red is in direction of decreasing range displacement (uplift). Dashed line indicates 30 mm subsidence contour from Figure 1A. Decline/recovery is ratio between periods of water-level decline (May 1 to September 15, see Fig. 3) and recovery (September 16 to April 30) for each interferogram. Interferograms A and B and interferograms C and D are constructed from different synthetic aperture radar (SAR) images; phase signatures present in A or B as well as in C or D represent deformation and not atmospheric artifacts (pairwise logic, e.g., Massonnet and Feigl, 1998). White-yellow-white wavelike phase signature appears only in upper left of C, and thus is artifact in March 1993 radar image.

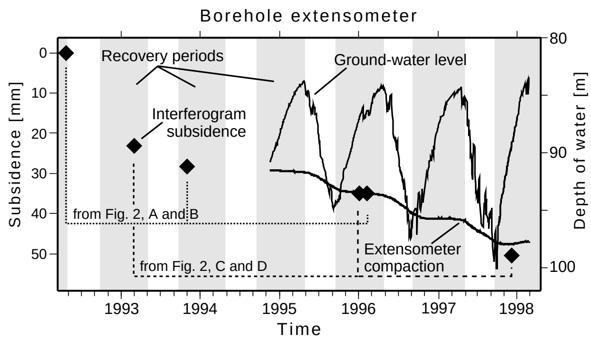

Figure 3. Interferometric synthetic aperture radar (InSAR) detected subsidence since April 1992 compared with borehole-extensometer measured system compaction and water-level changes since 1994. InSAR measured subsidence is averaged over 10 000 m². Compaction data are relative and shifted to InSAR measurement of 9 February 1996. InSAR data from Figure 2, C and D, are relative and shifted to compaction measurement of 4 January 1996. White and gray shadings indicate periods of water-level decline and recovery. January 1996–December 1997 interferogram measures 14 mm of vertical displacement and extensometer 12 mm for same period. Exact match is not expected because interferogram measures total subsidence whereas extensometer measures compaction of uppermost 245 m of system. Close agreement between two methods suggests that minimal compaction occurs beneath base of extensometer.

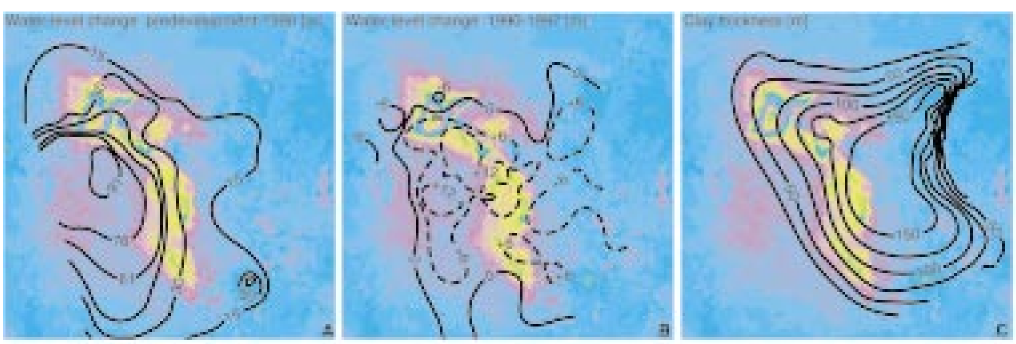

Figure 4. Water-level change (A) from predevelopment to 1990 (Wood, 1999), (B) from 1990 to 1997 (Las Vegas Valley Water District, 1997), and (C) aggregate clay thickness for two clay layers of Las Vegas Valley system (Morgan and Dettinger, 1996) superimposed on interferometric synthetic aperture radar detected land subsidence from Figure 1A. Water-level change maps show differences for given period. Maximum water-level declines may have been higher. Contour maps are based only on 50–100 point measurements.

tectonic creep as a cause of the deformation. The fault may separate more compressible deposits to the northwest from less compressible deposits to the southeast. It may also act as a barrier to ground-water flow, impeding the horizontal propagation of fluid-pressure changes and creating a discontinuity in water level across the fault. This is not evident on the water-level and clay-thickness maps, which are based on sparse point data and emphasize regional-scale features.

The occurrence of subsidence in the central subsidence zone, where water levels were in decline prior to 1990 but since have been in recovery or stable, suggests that residual compaction of slowly draining aquitards is the primary cause for land subsidence in this area. In the progressively subsiding northwest subsidence bowl, compaction is probably a response to continuous declines in water levels at the peak of the summer pumping seasons.

Within the central subsidence zone, differences in the magnitude and sense of displacement between interferograms appear to be related to the relative contributions of seasonal water-level decline and water-level recovery, as expressed by the decline/recovery ratio (Fig. 2). The April 1992–November 1993 interferogram (Fig. 2A) includes a longer period of decline than of recovery, whereas the opposite is true for the November 1993–February 1996 interferogram (Fig. 2B). The March 1993–January 1996 and January 1996–December 1997 interferograms (Fig. 2, C and D) include slightly longer periods of decline than recovery. The November 1993–February 1996 interferogram shows zero relative displacement (yellow) in areas shown as subsidence in the March 1993–January 1996 (30 mm—1 fringe) and January 1996–December 1997 (15 mm—0.5 fringe) interferograms. Taken together, the interferograms indicate that in the central zone subsidence occurs during periods of water-level decline and that some uplift occurs during periods of water-level recovery. This suggests that some of the deformation is elastic and fully recoverable. In areas of uplift (Fig. 2B), the seasonal elastic response more than compensates for any residual compaction.

This study shows that InSAR provides means to acquire spatial and temporal detail of land subsidence and aquifer-system deformation to aid ground-water management. The InSAR detected decrease in the subsidence rate since the early 1990s in the Las Vegas Valley demonstrates the role of artificial recharge in mitigating land subsidence. Continued slowing and ultimate arrest of subsidence will be dependent on sustaining low net ground-water pumping; sufficient to ultimately eliminate any residual pore-pressure deficits in the aquitards.

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Notes